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Laboratory Calibration of the CS655 Soil Moisture Sensor

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Laboratory Calibration of the CS655 Soil Moisture Sensor

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Energy and Earth Resources

The University of Texas at Austin

May 2016

Dedication

I dedicate this thesis to my mom for always encouraging me to be who I am and inspiring me to bloom where I am planted. Without my mom I would not be the person that I am today, so I am forever grateful for the strength, independence, and sense of purpose she has given me. Who could have known that allowing me to play in the dirt would lead to a career studying the Earth? And to Jilly and Andy for offering their unconditional support.

Acknowledgements

I would like to thank my advisor, Michael Young, for guiding me through my research and supporting me in every aspect of this journey. I am grateful for his invaluable advice and wisdom that has motivated me as a student and will continue to inspire me throughout my career. It has been a privilege working with Michael and I am grateful for the opportunity to do so.

I would also like to thank my co-advisor, Todd Caldwell, for his patience both in the lab and in the office. I would like to thank Charlie Kreitler as well for teaching me about the multifaceted management of water resources in Texas. I would also like to acknowledge my favorite cube-mate, Chuck, for making this process a little bit easier with his patience, encouragement, and friendship.

Abstract

Laboratory Calibration of the CS655 Soil Moisture Sensor

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Calibration of a frequency domain reflectometer (model CS655, Campbell Scientific, Inc. Logan, UT) is presented using five distinct soil types and three different calibration methods. Frequency domain reflectometers estimate soil water content (SWC) using electromagnetic properties of the surrounding media. Few, if any, sensors directly measure volumetric water content. Instead, a sensor's output must be converted either by a universal or a user-specific calibration equation. These sensors are used for a variety of applications using a factory-supplied equation with an error of 0.03 $m^3\,m^{-3}$. Soil specific properties such as clay content and salinity can affect their performance in field situations. A site or soil specific calibration can provide more accurate measurements albeit at greater time and expense. For this research, three calibration methods on five central Texas soils were evaluated to determine soil-specific calibration equations. First, a standard calibration method was performed by packing soil cores with soil at progressively higher SWC, inserting the probe vertically, and taking repeated measurements. Next, an upward

infiltration method was used to slowly introduce water at the bottom of the soil core performed on soil cores with vertically inserted probes. Lastly, a downward infiltration method was performed by introducing known amounts of water to the top of the soil core with a vertically inserted probe and allowing infiltration and redistribution between subsequent water additions. The data from all three methods were fitted to a third-order polynomial, based on the relationship between the dielectric permittivity and the SWC. Overall, the CS655 performance across all five soils improved from a root mean square error (RMSE) of 0.065 and 0.042 m^3m^{-3} using standard and downward calibrations, respectively, to 0.026 and 0.024 m^3m^{-3} using a site-wide calibration. Results further indicate that the soil-specific calibration curves provide better fits than the commonly-used Topp's equation, and that the coefficients in the soil-specific curve differ significantly ($p<0.05$). The research presented here improves our understanding of the CS655 sensor, and the calibration curve needed to improve field-based measurements currently occurring across the Texas Soil Observation Network.

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Chapter 1: Introduction

1.1 BACKGROUND

Soil moisture is an essential environmental, hydrological, and climate variable. Soil moisture is quantitatively measured as volumetric water content (a percentage of the total soil volume) and referred hereafter as soil water content (SWC). Knowing SWC is imperative to understanding other phases of the global water cycle, such as climate prediction and the energy and water balance and can help manage water resources. Knowing the SWC enables better understanding of the distribution of water within a soil profile and the resultant responses to those conditions. Continuous measurement of SWC can provide information on its spatial and temporal variability that can help predict patterns of water flow within a region.

Climate prediction is substantially improved from SWC data, and meteorologists and climate scientists can predict water fluxes (e.g., precipitation, evaporation and transpiration) when initiated with better soil moisture. Enhanced SWC observations can help weather forecasts because precipitation and air temperature are two resultant factors of SWC (Koster et al., 2011). A deficit in SWC can portend drought and high antecedent SWC before a storm event can exacerbate floods (Famiglietti et al., 1999). The amount of water that evaporates from the land surface into the atmosphere depends on the soil moisture, which also is the key to understanding both the water and energy cycles (Robinson et al., 2008).

SWC information can also help manage water resources more efficiently, like effective irrigation scheduling for improved agriculture. The timely application of water, based on knowledge of existing soil moisture conditions, can optimize crop production. Quantifying SWC can determine optimum irrigation timing and amount (Lukangu et al., 1999).

However, SWC has a high spatial variability due to its influence by various land surface and meteorological factors at different scales (Warrick et al., 1977; Russo et al., 1980; Vachaud et al., 1985; Kachonoski et al., 1988). The challenge, thus, is to match the scale of measurement to the scale of interest. For example, point-scale SWC measurements differ from the scale represented by a watershed or global model grid cell, and therefore the volumetric water content values at these scales may be affected by the upscaling or averaging that is needed to match scales (Robinson et al., 2008). Also, specific site locations (at the point scale) may be time-stable, but the site as a whole (watershed/catchment scale) may not be time-stable. Time stability is defined as the time invariant association between spatial locations and classical statistical parametric values (Vachaud et al., 1985). This difference in temporal variation creates challenges when evaluating soil moisture data and determining SWC, because time stability for SWC is scale dependent.

A data validation challenge is reducing the mismatch between the point measurements from *in-situ* SWC estimates and the regional estimates from remote sensing (Cosh et al., 2004). Point measurements can be used to investigate sites that consistently exhibit mean behavior irrespective of the overall wetness (Grayson et al., 1998), and is the product of various hydrological processes. Remotely sensed SWCs provide information on the average soil moisture conditions within a pixel (a unit of data collection that represents the relative reflected light energy). The extent of within-pixel variability affects how well the remotely sensed measure reflects actual moisture conditions within the pixel (Mohanty et al., 2001).

Several methods are available for determining SWC both on the ground and by remote sensing via satellite. Ground-based methods for estimating SWC include gravimetric sampling, nuclear moderation techniques, and electromagnetic systems.

Gravimetric sampling is the most accurate method for estimating SWC; however, it is extremely time consuming and destructive (Cosh et al., 2005; Vaz et al., 2013). This method involves collecting soil samples from the field and determining the water content of the soil by oven drying at 105°C for at least 24 hours. The product of this gravimetric water content and the soil bulk density is the volumetric water content, which is the unit of choice when considering SWC. Nuclear moderation techniques (e.g., neutron probe) operate through the process of neutron scattering, in which "fast" neutrons emanating from the probe through radioactive decay of Americium, are slowed by collisions with hydronium molecules; a higher number of "slow" neutrons is correlated to a higher water content (Schmugge et al., 1980). This method requires an operator at all times and a permit, due to the use of radioactive materials, both of which have some disadvantages, but the technique itself has been the standard for field measurements for nearly 50 years (Belcher et al., 1950). Electromagnetic techniques include those methods that depend on the effect of moisture on the electrical properties of soil (Topp et al., 1980). Two popular classes of electromagnetic sensors used to estimate SWC are time domain reflectometry (TDR) and frequency domain reflectometry (FDR). Both sensor classes convert dielectric properties of the bulk soil into water content (Jones et al., 2005).

Satellite remote sensing methods for estimating SWC infer volumetric water content through the soil's influence on electrical potential fields, such as electromagnetic or gravitational. Electromagnetic remote sensing depends on the measurement of electromagnetic energy that has either been reflected or emitted from the soil surface; this is often known as active or passive respectively. Electromagnetic sensors are beneficial because they are rapid; however, they are prone to bias. Gravitational remote sensing such as NASA's Gravity Recovery and Climate Experiment (GRACE), observes satellite orbit perturbations that are caused by gravitational anomalies near the land surface (Tapley et al., 2004). GRACE maps Earth's gravity field by measuring the distance between two identical spacecraft using GPS and a laser ranging system.

Although the ground-based methods have been shown to provide reliable estimates of SWC, differences in soil specific or site specific properties influence these estimates, which decreases their validity. Often, a user-derived calibration is necessary for *in-situ* sensors to improve accuracy of the measurements and ensure confidence in the SWC estimates. *In-situ* soil moisture networks that use a point-measurement system over a defined area can be used to ground-truth satellite remote sensing estimates of SWC. Here, ground-truthing connects point-scale measurements to the inferred SWC estimates collected from satellite remote sensing. Gravimetric sampling and laboratory experiments can be used to calibrate point measurements, such as those made by electromagnetic sensors.

There are many different types of electromagnetic SWC sensors including time domain reflectometry (TDR), frequency domain reflectometry (FDR), capacitance sensors, and impedance sensors. These sensors have different calibration functions depending on their operating frequencies (Robinson et al, 2008; Vaz et al., 2013). The velocity of electromagnetic wave along the probe waveguides for both TDR and FDR depends on the dielectric permittivity of the material surrounding the rods. FDR sensors operate at a lower frequency (15 to 175 MHz) (Seyfried et al., 2001; Vaz et al., 2013) than TDR sensors (0.5 to 1 GHz) (Robinson et al., 2008). Capacitance sensors measure the capacitance of a circuit which uses the medium surrounding the sensor as the dielectric material (Vaz et al., 2013). Capacitance sensors operate at a much lower frequency between 0.10 and 0.25 GHz (Robinson et al., 2008). Impedance sensors measure the impedance of the sensor embedded in a medium and operate at a frequency between 5 and 150 MHz (Robinson et al., 2008).

As frequency decreases, so does the sensor cost but also at the expense of increased effects related to imaginary permittivity related to bound or immobile water and soil conductivity.

The sensor used in this research is the frequency domain reflectometry (FDR) probe (model CS655, Campbell Scientific, Inc., Logan, UT). The CS655 is based on the principle that the velocity of electromagnetic wave propagation along the probe waveguides depends on the dielectric permittivity of the soil material surrounding and between the waveguides. The CS655 consists of two 12 cm stainless-steel rods connected to a printed circuit board (Figure 1.1). The rod diameter is 3.2 mm and the rod spacing is 32 mm. The probe's circuit board is encapsulated in epoxy and a shielded cable is attached to the circuit board for data logger connection. The sensor measures propagation time, signal attenuation, and temperature. Dielectric permittivity, volumetric water content, and bulk electrical conductivity are then derived from these raw values. Measured signal attenuation is used to correct for the loss effect on reflection detection, and thus propagation time measurement. (Campbell Scientific, 2015). This loss-effect correction allows accurate water content measurements in soils with solution electrical conductivity (EC) ≤ 8 dSm^{-1}. The approximate measurement area in soil extends approximately 7.5 cm from the rods along their length and 4.5 cm beyond the ends of the rods (Campbell Scientific, 2015). An onboard thermistor provides a point measurement of the temperature within the epoxy of the probe head, but not within the soil material itself. For the CS655 probe, and nearly all other similar probes, a user-derived calibration curve improves the accuracy of the volumetric water content measurement because soil properties are taken into account (Gardner et al., 1998; Cosh et al., 2005; Loiskandl et al., 2010; Sakaki et al., 2011).

1.2 PROBLEM STATEMENT

This research focused on the calibration of the CS655 water content reflectometer using five different soil materials of different textures and three different laboratory methods. Soil material was collected from the Texas Soil Observation Network (TxSON), located near Fredericksburg, Texas. The overall question to be addressed is whether the conversion from dielectric permittivity to soil water content is improved using a soil-specific calibration curve, versus a factory-specific curve that was supplied with the sensor. The calibration results will better convert responses from NASA's Soil Moisture Active Passive (SMAP) satellite into reliable volumetric water content values.

1.3 THESIS ORGANIZATION

The remainder of this thesis is divided into three chapters. Chapter 2, the literature review, provides a summary of topics including estimating SWC at different scales and methods of sensor calibration. Chapter 3 was designed as a standalone manuscript of this thesis. Along with the abstract at the beginning of this thesis, Chapter 3 will be submitted as a manuscript to the Vadose Zone Journal. Lastly, Chapter 4 discusses the future of soil moisture monitoring networks.

Figure 1.1. CS655 Soil Water Content Sensor. The electronics are identical to the CS650 sensor except that the probe length is decreased from 30 to 12 cm which improves installation and accuracy in higher conductivity soils.

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Chapter 2: Literature Review

2.1 ESTIMATING SOIL WATER CONTENT AT DIFFERENT SCALES

2.1.1 Ground-Based Estimates of Soil Water Content

Soil bulk density is the mass per unit volume of soil:

$$\rho b = {}^{M_s}/_{V_T} = {}^{M_s}/_{V_s + V_a + V_w} \qquad \textbf{2.1}$$

where ρb is the bulk density, M_s is the mass of the solids, and V_t is the total soil volume (volume of the solids, volume of the air, and volume of the water) (Hillel, 2004). The bulk density is used to characterize the structure of a soil sample, including the degree of compaction, or the shrinking/swelling potential in a clay soil. In relation to this research, the bulk density is used to convert SWC data from a mass to a volume basis using the following equation:

$$\theta_v = \theta_g * \rho_b \qquad \textbf{2.2}$$

where θv is the volumetric water content and θg is the gravimetric water content (Hillel, 2004). The gravimetric water content is determined by measuring the wet mass of a soil sample, oven drying the soil sample at 105°C for at least 24 hours, and then measuring the dry mass of the soil sample (Topp and Ferre, 2002). The gravimetric water content can then be calculated (Topp and Ferre, 2002):

$$\theta_g = \frac{m_{wet} - m_{dry}}{m_{dry}} \qquad \textbf{2.3}$$

Electromagnetic techniques include those methods that depend on the effect of moisture on the electrical properties of soil (Jones et al., 2005). Electromagnetic approaches take advantage of the moisture dependence of the soil dielectric properties. Dielectric properties of soil are characterized by a frequency dependent complex dielectric response function:

$$\varepsilon(w) = \varepsilon_r(w) + j\varepsilon_i(w) \qquad \textbf{2.4}$$

where $\varepsilon_r(w)$ is the real part of ε, $\varepsilon_i(w)$ is the imaginary part of ε, j is the square root of -1, and w is the angular frequency (Bottcher, 1952). The values of dielectric permittivity for soil are typically between 3 and 5 (Topp et al., 1980), the value for water at room temperature is about 80.2 (Archer et al., 1990), and the value for air is 1 (Maryott et al., 1953). Relatively small amounts of free water in soil will greatly affect its electromagnetic properties. This dependence of dielectric properties of soil on water content can be used by either *in-situ* or remote sensors (Schmugge et al., 1980).

Time domain reflectometry (TDR) and frequency domain reflectometry (FDR) are two similar variations on the theme of converting electromagnetic wave propagation to SWC. TDR became established as a nondestructive method for determining SWC in the 1970s and early 1980s (Chudobiak et al., 1979; Patterson et al., 1980; Topp et al., 1981, 1984, 1985; Dalton et al., 1986; Ledieu et al., 1986; Baker et al., 1987). TDR measures the change in electromagnetic signal velocity as it travels through the soil. The velocity of the electromagnetic wave varies with apparent dielectric constant (Topp et al., 1980). TDR can be used to determine SWC because the dielectric constant in soil is strongly related to its water content (Schmugge et al., 1980).

The velocity of electromagnetic wave propagation along the probe waveguides for both TDR and FDR depends on the dielectric permittivity of the material surrounding the rods. The real part of this permittivity, ε, related to the behavior of a dielectric, and the imaginary component, ε_i, is a consequence of energy loss due to electrical conduction or other processes (Gardner et al., 1998). Because soil is an imperfect dielectric possessing electrical conductance, the imaginary component is not negligible. Subsequently, permittivity is referred to as the relative permittivity (the permittivity relative to that of free space), and is calculated as:

$$\varepsilon_{ra} = \left(\frac{ct}{2L}\right)^2 \qquad \textbf{2.5}$$

where ε_{ra} is the relative permittivity, c is the speed of light, t is time, and L is the distance the pulse travels (Topp et al., 2002).

Increases in voltage resulting from signal attenuation are corrected using an electrical conductivity measurement. A calibration equation converts period and electrical conductivity to bulk electrical permittivity (Campbell Scientific, 2015). One such relationship between dielectric permittivity and volumetric water content in mineral soils has been described by Topp et al. (1980), who suggested an empirical equation using a third-order polynomial:

$$\theta_v = -5.3*10^{-2} + 2.92*10^{-2}\,\varepsilon_{ra} - 5.5*10^{-4}\,\varepsilon_{ra}{}^2 + 4.3*10^{-6}\,\varepsilon_{ra}{}^3 \qquad \textbf{2.6}$$

where θ_v is the volumetric water content and ε_{ra} is the bulk dielectric permittivity of the soil (Topp et al., 1980). This general calibration curve was created using measurements from many different mineral soils and other materials, with a reported error of ± 0.02

m^3m^{-3} using TDR. FDR sensors, like the CS655, operate at a lower frequency causing the imaginary component of the permittivity to play a more important role in determining water content; this is why a soil-specific calibration is generally used when higher accuracy is needed (Udawatta et al., 2011). In addition, because different soils alter the behavior of dielectric probes, soil-specific or user-defined calibration curves are often recommended to reduce error and uncertainty in the water content measurements (Seyfried et al., 2005; Robinson et al., 2008).

The Topp equation (1980) underestimates the water content of some organic, volcanic, and fine textured soils. Additionally, porous media with porosity greater than 0.5 or bulk density greater than 1.55 g cm^{-3} may require a media-specific calibration equation (Topp et al., 1980). In these cases, the user may develop a calibration equation to convert CS655 permittivity to volumetric water content over the range of water contents the probe is expected to measure (Campbell Scientific, 2015).

The quality of SWC measurements that apply electromagnetic fields to waveguides is predominantly affected by changing dielectric permittivity due to changing water content, but is also affected by electrical conductivity (Rhoades et al., 1976). Free ions in the soil solution provide electrical conduction pathways that attenuate the signal applied to the waveguides. Bulk electrical conductivity increases with water content, when sufficient ions are present in the liquid phase. Dielectric permittivity also changes with temperature (Rhoades et al., 1976). The effect of temperature on soil permittivity is related to soil specific properties such as porosity and the permittivity of the soil solid phase with temperature (Rhoades et al., 1976).

2.1.2 Satellite Remote Sensing Estimates of Soil Water Content

Mohanty et al. (2013) summarizes recent advances in calibrating and validating microwave remote sensing for ground-based SWC measurements. Their study emphasizes that ground validation is an important requirement for all remotely sensed land surface attributes. The remote sensing of SWC depends on the measurement of electromagnetic energy that has either been reflected or emitted from the soil surface. The variation in intensity of this radiation with SWC depends on the dielectric properties, soil temperature, or a combination of both. The particular property that is important depends on the wavelength region being considered. For example, properties of soil that depend on water content, like thermal and dielectric properties, are accessible to remote sensing at the thermal infrared wavelength, 10 μm, (30,000 GHz) and microwave wavelength, 10,000 – 500,000 μm, (30,000 to 600 GHz) wavelengths (Schmugge et al., 1978). The thermal infrared approach consists of measuring the diurnal range of surface temperature or measuring the crop canopy-air temperature differential. The amplitude of the diurnal range of soil surface temperature is a function of both internal and external factors. The internal factors are thermal conductivity, heat capacity, and thermal inertia, which are measures of the thermal mass and the velocity of the thermal wave that control the surface temperature of the material. The external factors are meteorological such as solar radiation, air temperature, relative humidity, cloudiness, and wind. Thermal inertia is an indication of the soil's resistance to the driving force of the meteorological conditions. An increase in SWC causes an increase in the heat capacity, thermal conductivity, and the resulting thermal inertia (Schmugge et al., 1980).

The active microwave approach consists of measuring the radar backscattering coefficient, which is a measure of the intensity of the pixel that is returned from the radar. The backscattering coefficient provides the differential scattering cross section per unit volume (Schmugge et al., 1980; Jackson and Schmugge, 1986). The passive microwave measures the microwave emission or brightness temperature. Because the dielectric properties of a medium determine the propagation characteristics for electromagnetic waves in the medium, they will affect the emissive and reflective properties at the surface. These properties depend on the SWC, which can be measured in the microwave region of the spectrum by radiometric (passive) and radar (active) techniques (Schmugge et al., 1980; Jackson and Schmugge, 1986.).

Satellite remote sensing is a popular technique for estimating SWC. Famiglietti et al. (1999) investigated ground-based soil moisture variability within remote sensing footprints. Portable SWC probes were used to monitor SWC at six experimental sites in central Oklahoma (Figure 2.1). The wide spatial distribution of the sites, combined with the intensive, near-daily monitoring, provided a unique opportunity, relative to previous smaller-scale and shorter-duration soil moisture studies, to characterize variations in surface SWC over a range of wetness conditions. Results indicated that distinct differences in mean SWC between the sites are consistent with variations in soil type, vegetation cover, and rainfall gradients (Famiglietti et al., 1999).

Cosh et al. (2004) used watershed scale SWC measurements to validate the Advanced Microwave Scanning Radiometer (AMSR) remote sensing satellite. *In-situ* SWC probe measurements from the existing network as part of the Soil Moisture Experiment 2002 (SMEX02) in Iowa were used. The study region of SMEX02 was the Walnut Creek watershed and the surrounding area (100 km^2) located south of Ames, Iowa (Figure 2.2). A total of 12 SWC probes were installed in 10 study fields that captured a variety of land cover conditions within the watershed. The results establish the validity of this approach to provide watershed scale soil moisture estimates in this study region for the purposes of satellite validation (Cosh et al., 2004).

Vivoni et al. (2008) compared ground-based surface SWC estimates and remotely sensed SWC estimates to evaluate remote sensing capability and its spatiotemporal variability during the Soil Moisture Experiment 2004 (SMEX04) located in northern Sonora, Mexico (Figure 2.3). The study focused on a ~100 km^2 basin draining into the Rio San Miguel, a mountainous area with complex topography and elevation gradients, in which previous research of this type was lacking. The remotely sensed SWC was estimated from an aircraft-based Polarimetric Scanning Radiometer and the ground-based SWC was estimated from *in-situ* sampling using an electromagnetic soil moisture probe. A total of 30 sites along a transect with varied elevations were sampled daily, coinciding with the aircraft flights, during the study period (August 3 to 14, 2004). Comparison of the two water content estimation methods was used to evaluate remotely sensed estimates relative to ground observations. Results indicate that the SWC estimates from the ground-based and remotely sensed data reveal consistent variations with elevation (Vivoni et al., 2008).

The previously mentioned research (Famiglietti et al., 1999; Cosh et al., 2004; Vivoni et al., 2008) demonstrates the use of ground-based SWC measurements to validate remotely sensed measurements. The research described herein uses the calibration of a new SWC sensor (model CS655, Campbell Scientific Inc., Logan, UT) to validate the SWC estimates measured throughout the TxSON network and by NASA's Soil Moisture Active Passive (SMAP) satellite, which is an orbiting observatory that measures the amount of water in the top 5 cm of soil everywhere on Earth's surface (SMAP Handbook, 2015). SMAP is designed to measure soil moisture over a three-year period, every 2 to 3 days, allowing changes to be observed over time scales ranging from major storm events to repeated measurements of changes over the seasons (SMAP Handbook, 2015). Where the ground is not frozen, SMAP measures the amount of water found between minerals, rocky material, and organic particles found in the soil. SMAP will produce global maps of soil moisture. SMAP can help scientists monitor drought, predict floods, assist crop productivity, weather forecast, and link water, energy, and carbon cycles (SMAP Handbook, 2015).

2.2 METHODS OF SENSOR CALIBRATION

Gravimetric sampling is the most accurate method for wide-scale SWC estimates; however, it is time intensive and only provides water content in a snapshot in time, rather than measurement techniques that capture temporal variability. Soil moisture probes (such as TDR or FDR) can be used to estimate SWC more quickly and easily. However, these instruments require a conversion between the sensor output and SWC. Therefore, it is necessary to calibrate the instruments to accurately validate *in-situ* measurements to gravimetric samples.

2.2.1 Standard Calibration

Variations in bulk density, soil texture, and surface conditions all have some impact on calibration. Cosh et al. (2005) compared three different methods for impedance probe calibration (general calibration, soil classification specific calibration, and field specific calibration) and conclusions were drawn about the accuracy of the probes and calibrations for large scale experiments. The study used data from two Soil Moisture Experiments: SMEX02 was conducted in central Iowa and SMEX03 was conducted in Oklahoma (Figure 2.4).

The first method used was general calibration that resulted in a higher SWC (Cosh et al., 2005). The second method is a soil specific calibration, which requires gravimetric samples to be collected coincident with probe measurements for each soil type. The third method is field specific calibration that requires sampling for each study location, generating field-site specific coefficients for the calibration equation (Cosh et al., 2005).

Results from the study show that impedance probes require calibration to reduce errors and remove significant bias, which was expected. The root mean square error (RMSE) and bias of the soil specific calibration and the field specific calibration curves were improved compared to the general calibration, with the field specific calibration proving to be the most accurate method (Cosh et al., 2005; Vaz et al., 2013).

The objective of the study by Vaz et al. (2013) was to evaluate the performance of eight commercially available electromagnetic moisture sensing systems in seven well-characterized and texturally varying soils using a standardized approach. Soil samples were compacted into polycarbonate containers (12 cm inner diameter, 20.3 cm tall) at varying water contents from oven dry to relatively wet conditions (0.35 m^3 m^{-3}) in 0.05 m^3 m^{-3} steps. The container diameter was chosen based on the instrument with the largest measurement volume to ensure that wall effects were minimized or eliminated. Reference bulk density values were determined for each soil by packing oven-dried soil into the polycarbonate containers, defining the reference dry mass for each soil. Water was then added incrementally to obtain target volumetric water contents based on the container total volume. At each increment, the water was thoroughly mixed with a similar mass of dry soil and packed into the columns at similar densities. Gravimetric water content was determined by oven-drying of the soils at 105°C for at least 24 hours after measurements with the electromagnetic sensors were completed (Vaz et al., 2013).

Average values of the dielectric permittivity, voltage, or period were plotted against measured volumetric water content to evaluate the performance of the sensor using the factory-supplied calibration equations. Root mean squared deviations (RMSD) of the SWC determination with factory-supplied and soil-specific equations were computed to assess quality-of-fit and accuracy. Sensor reproducibility was evaluated by the coefficient of variation (CV) (ratio of the standard deviation to the mean), which was obtained from replicate measurements for all soil samples across the range of measured SWC (Vaz et al., 2013). Results found a significant difference in the factory derived calibration curves and the calibration curves derived during the study. Vaz et al. (2013) suggests that the procedure used in the study would be sufficient as a standardized laboratory protocol for SWC electromagnetic sensor calibrations.

2.2.2 Upward Infiltration

Young et al. (1997) used the upward infiltration method to calibrate TDR probes based on the upward flow method used by Hudson et al. (1996) to determine soil hydraulic property functions. Three distinct soil types were used: Vinton fine sand, Casa Grande sandy loam, and Pima silt loam, and three upward infiltration experiments per soil type were performed (9 total). A polycarbonate soil column was uniformly packed with air-dried soil and passed through a sieve with 2 mm openings to bulk densities similar to those found in the field. The TDR probes were inserted vertically into the soil column and were connected to a TDR cable tester which stored the data on a computer. The soil column was placed on a digital balance to record weight measurements. Paired values of TDR traces and soil column weights were acquired every three minutes. Each experiment was run between 7 and 13 hours, collecting between 140 and 260 paired values, until water was seen leaking from the upper entry ports for the TDR probe. The volumetric water content at the end of each experiment was measured by oven drying the soil at 105°C for 72 hours and converting the gravimetric water content to a volumetric basis using the measured bulk density. Traditional calibration experiments were performed to compare the results with the upward infiltration experiments.

Comparison of the standard method (Topp et al., 1980) calibration data with the upward infiltration method data shows good results. The upward infiltration method for calibrating TDR probes was successful and offers the advantage of collecting more data in a quicker timeframe. Since Young et al. (1997) was published, other scientists have used the same method for calibrating electromagnetic sensors. Seyfried et al. (2005) used upward infiltration to calibrate the Hydra Probe (FDR) soil moisture sensor. Loiskandl et al. (2010) used upward infiltration to calibrate four different electromagnetic soil moisture probes. Burns et al. (2014) used a version of the upward infiltration method to calibrate the same Hydra Probe (FDR) soil moisture sensor. The results from all three of these studies, show that site-specific or soil-specific upward infiltration calibration provide superior accuracy to manufacturer calibration.

2.2.3 Downward Infiltration

Quinones et al. (2003) applied three different methods for calibrating a TDR probe using three soil types. These methods include a discontinuous process (standard calibration), a process using continuous dripping similar to the upward infiltration process described by Young et al. (1997), but introducing the water from the top of the column (downward infiltration), instead of the bottom, and a proposed process that is a combination of both methods. For all methods, soil columns were prepared by oven-drying the samples, sieving the soil to a 1.2 mm diameter, and packing the soil in a 30 cm high, 9.5 cm diameter Plexiglas cylinder. The downward infiltration method introduced water from the surface of a packed soil column, avoiding water addition that would exceed the infiltration capacity of the soil. A sensor was progressively introduced into the soil sample with a known moisture content. The three methods led to similar consistent relationships and were validated using field data (Quinones et al., 2003).

Rudiger et al. (2009) developed a general calibration equation for the CS616 (the predecessor of the CS655 used here) water content reflectometer using *in-situ* field measurements and laboratory measurements. The sensors were installed at 26 soil moisture monitoring sites throughout the Goulburn River catchment, in New South Wales, Australia and subsequent soil samples were extracted. The soil columns were prepared using a 40 cm high, 15 cm diameter container and then inserting the probe vertically. A downward infiltration method was used to maintain the pore structure and density of each sample, and the sensor orientation during the experiments. Water was added from the top of the container and allowed time to fully infiltrate into the column while measurements were recorded. The resulting calibration equation indicates that the site-specific calibration is more accurate than the factory-supplied calibration, especially for finer soils (Rudiger et al., 2009).

Burns et al. (2014) compared three different methods for calibrating the Stevens Hydra Probe: mixed cell (standard), wet-up (upward infiltration), and dry-down. Burns et al. (2014) points out that wet-up or dry-down calibrations are more representative of permanently installed sensors, since these methods record measurements across a range of SWCs, but at a constant bulk density. A total of 18 soil samples with a range of textures were collected from agricultural fields located in central Saskatchewan, Canada at 5, 20, and 50 cm depths. The oven-dried soils were packed into glass beakers at a density similar to the field bulk density. The probe was inserted vertically into the soil core and connected to a data logger that recorded continuous measurements at 15 minute intervals. The beaker was placed on a balance that took weight measurements coincident with probe measurements. The dry-down method is a modification of the wet-up method, where the saturated soils from the wet-up experiments are allowed to dry and the weight is continuously recorded. A small fan was positioned near the soil column, and a dehumidifier was placed in the laboratory to encourage evaporation. In contrast to the factory-supplied calibration, site-specific calibrations using both the wet-up and dry-down methods resulted in better accuracy (lower RMSEs) (Burns et al., 2014).

This research evaluates the next generation of Campbell Scientific, Inc. (CSI) water content reflectometers (CS655), the successor to the CS615 and CS616 sensors which all estimate soil water content from a two-way travel time. Many factors such as soil temperature, texture, and bulk electrical conductivity can influence the performance of these sensors resulting in soil-specific errors greater than the manufacturer's reported estimate. For this research, three different calibration methods and five different soils were evaluated to determine sensor performance and soil-specific calibration curves.

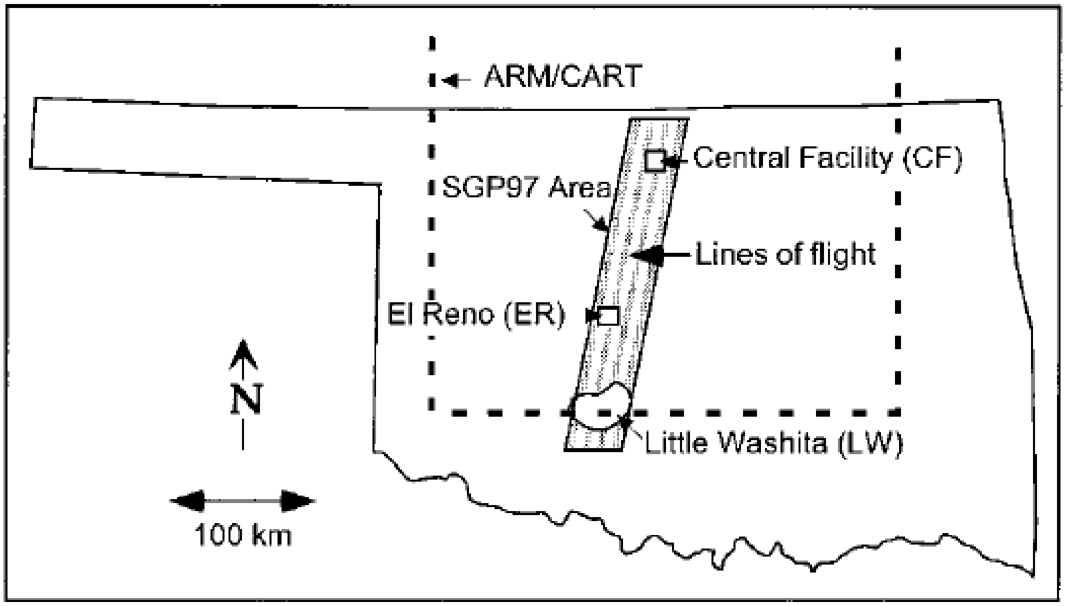

Figure 2.1. Location of the Southern Great Plains 1997 Hydrology Experiment. (from Famiglietti et al., 1999)

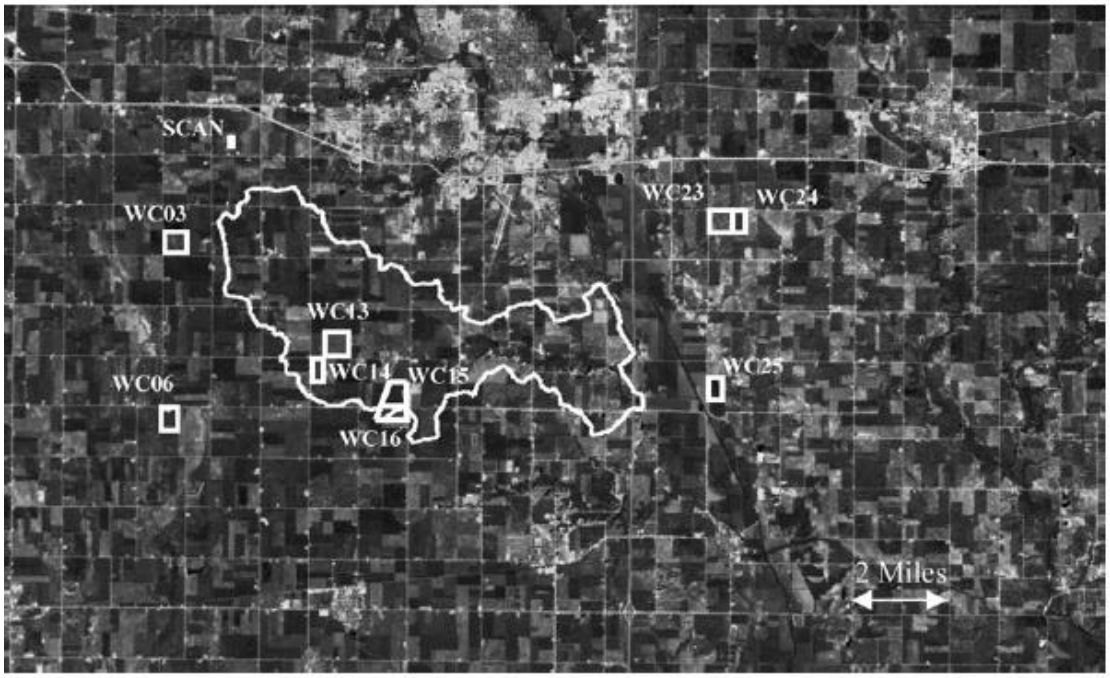

Figure 2.2. An outline of the Walnut Creek watershed shown over a greyscale TM image from July 1, 2002 and field study sites (labeled white squares) (from Cosh et al., 2004).

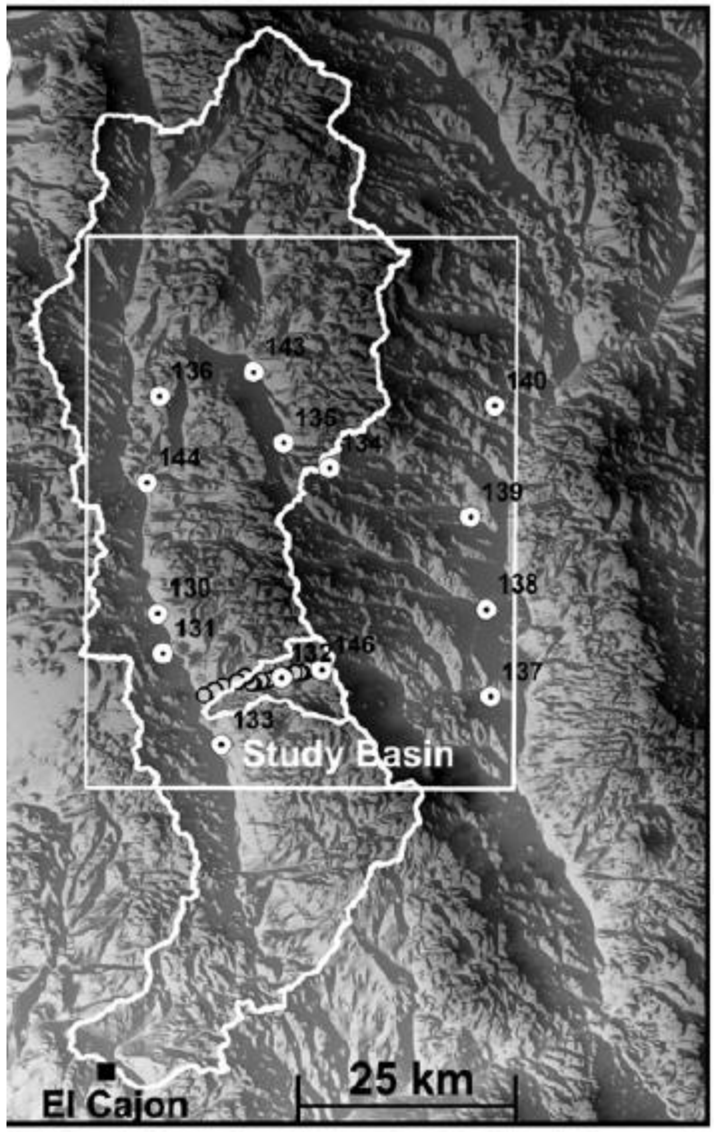

Figure 2.3. Regional SMEX04 study area in northern Sonora, Mexico including sampling points (numbered white circles) (from Vivoni et al., 2008).

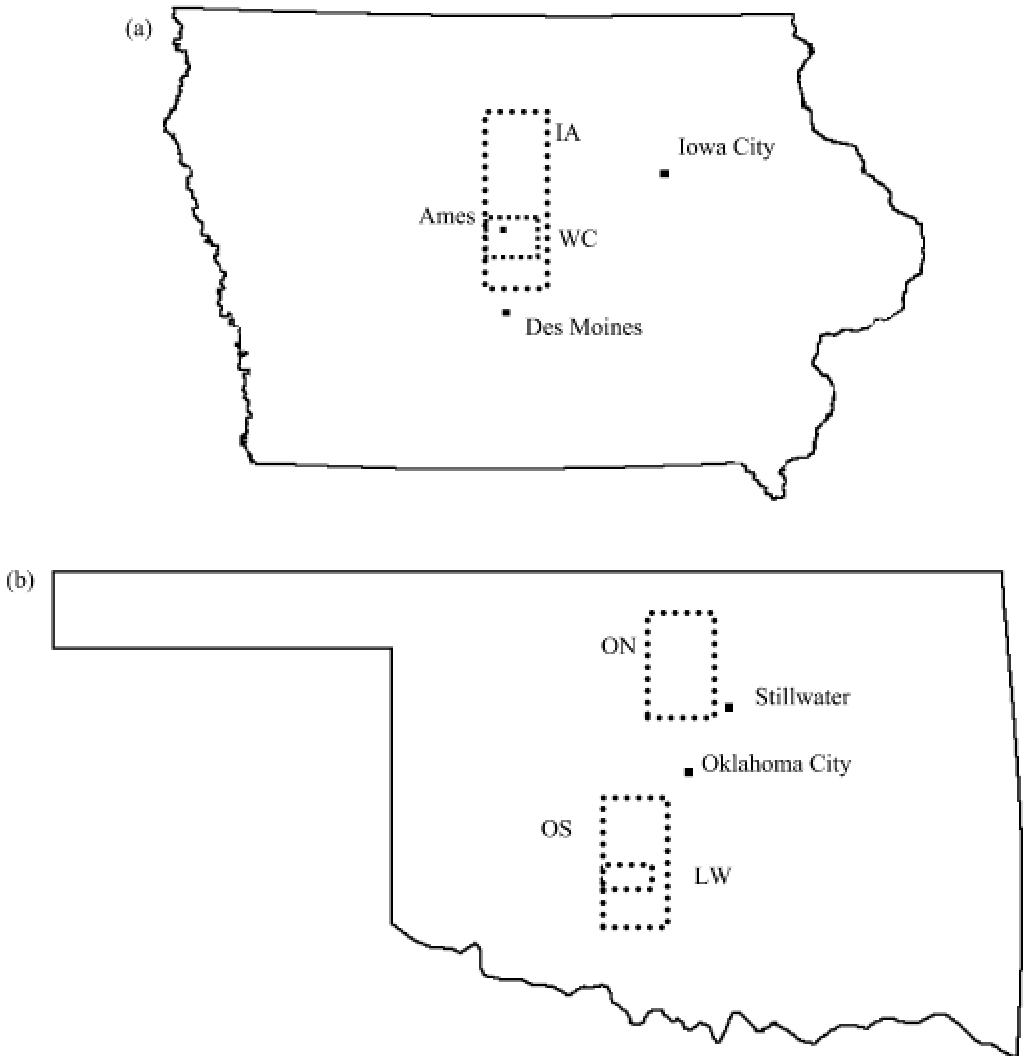

Figure 2.4. (a) SMEX02 location in Iowa. (b) SMEX03 location in Oklahoma (from Cosh et al., 2005).

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Author's note: The following manuscript (Chapter 3) will be submitted to the Vadose Zone Journal. The abstract at the beginning of this thesis accompanied the submitted manuscript.

Chapter 3: Laboratory Calibration of the CS655 Water Content Reflectometer

3.1 Introduction

The ground-based estimate of surface soil water content (SWC) over large areas is an important aspect of hydrology, especially for satellite validation. Gravimetric sampling is the only method which directly measures SWC; however, it is a time intensive and destructive point measurement (Cosh et al., 2005; Vaz et al., 2013). Electromagnetic-based techniques responding to soil dielectric permittivity are advantageous because they do not use ionizing radiation (such as neutron scattering), they are non-destructive, they allow for continuous monitoring and recording of SWC ranging from dry to saturated conditions, and they can be applied to most soil types (Vaz et al., 2013). As with any sensor, however, acceptable use for measuring a physical parameter depends on the ability to calibrate sensor response. Fortunately, numerous investigators (e.g., Schmugge et al., 1980; Topp et al., 1980; Dalton et al., 1986; Young et al., 1997; Cosh et al., 2005; Vaz et al., 2013) have reported on the successful use of electromagnetic sensors to determine SWC for various materials.

The CS655 (Campbell Scientific, Inc., Logan, UT), an electromagnetic sensor, and more specifically, a frequency domain reflectometer, was used in this research to measure SWC. The CS655 functions based on the principle that the velocity of the electromagnetic wave propagation along the sensor waveguides depends on the dielectric permittivity of the material surrounding and between the waveguides (Campbell Scientific, 2015). SWC is derived from the sensitivity of the sensor to the dielectric permittivity of the medium surrounding waveguides, which form an open-ended transmission line. An oscillator state change is triggered by the return of a reflected signal from one of the waveguides, which are each connected to differential oscillators. The two-way travel time of the electromagnetic waves induced by the oscillator varies with changing dielectric permittivity (Campbell Scientific, 2015). The travel time of the reflected wave is correlated to SWC. Dielectric permittivity also changes with temperature (Rhoades et al., 1976). The effect of temperature on soil permittivity is related to soil specific properties such as porosity and the permittivity of the soil solid phase (Rhoades et al., 1976). An onboard thermistor provides a point measurement of the temperature within the epoxy of the sensor head, but not within the soil material itself.

To determine the electrical conductivity, the waveguides are excited with a known non-polarizing waveform and the signal attenuation is measured. On-board processing within the sensor calculates electrical conductivity from the signal attenuation measurements and combines the result with the oscillation period measurement to calculate the dielectric permittivity of the media and the SWC using the Topp's equation (Topp et al., 1980) (Campbell Scientific, 2015). The flow chart for internal operations and decision points of the CS655 is illustrated in Figure 3.1 with the equations listed in Table 3.1, and specific coefficients used to calculate permittivity listed in Table 3.2. A measurement of SWC with a CS655 begins with a raw reading of the input/output voltage ratio (VR) and pulse period (PA) as shown in Figure 3.1. If the VR is < 17, then bulk electrical conductivity (EC) is calculated using Equation 1. If EC is < 2.92 dSm^{-1} and the PA is > 0.84 μS, a probe-specific multiplier and offset are applied using Equation 2. The dielectric permittivity (Ka) is calculated using the manufacturer specified Equation 3. If the Ka > 0, but < 88, a probe-specific multiplier and offset are applied using Equation 4, which is converted to volumetric water content (θ) using Equation 5 which is essentially Topp's equation (Topps, 1980). The last step is to correct θ for temperature using Equation 6.

The propagation of electromagnetic waves is predominantly affected by changing dielectric permittivity due to changing water content, but it is also affected by electrical conductivity (Rhoades et al., 1976). Free ions in the soil solution provide electrical conduction pathways that attenuate the signal applied to the waveguides. Bulk electrical conductivity increases with water content, when sufficient ions are present in the liquid phase (Campbell Scientific, 2015).

While Topp's equation (Topp et al., 1980) has been determined to work well in a wide range of mineral soils, a user-derived calibration will improve accuracy of the volumetric water content measurement because soil properties are taken into account (Gardner et al., 1998; Cosh et al., 2005; Loiskandl et al., 2010; Sakaki et al., 2011). Topp's equation was shown (Topp et al., 1980) to underestimate the water content of some organic, volcanic, and fine textured soils. Additionally, porous media with porosity greater than 0.5 or bulk density greater than 1.55 g cm^{-3} may require a media-specific calibration (Topp et al., 1980).

The CS655 sensor is a relatively new, affordable low frequency sensor and it has not undergone rigorous testing. The sensor potentially makes significant advances from its predecessors, the CS615 and CS616, by estimating and correcting for bulk soil EC and temperature effects on permittivity. Therefore, the main objectives for this research are to:

(1) evaluate the performance of the CS655 in five soils of varying texture and EC using three different calibration methods:
    a. standard calibration,

b. upward infiltration,

c. downward infiltration;

(2) characterize the five soil types used during calibration; and,

(3) evaluate the accuracy of the factory supplied calibration, versus that determined through soil-specific calibration.

3.2 METHODS AND MATERIALS

3.2.1 Study Area and Soils

Gillespie County is on the Edwards Plateau, a terrain characterized by uplifted Cretaceous limestone deeply incised by perennial and ephemeral stream as the Texas coastal plains to the east subsided along the Balcones Escarpment. Often referred to as the Texas Hill Country, this area was formed as the eastern and southern margins of the Balcones Fault Zone eroded after its displacement. The main bedrock unit underlying the Hill Country is the Glen Rose Formation that exhibits a “stair-step” topography of limestone and dolomitic beds (Wilcox et al., 2007). Soils on the risers are Udic Calciustolls or Petrocalcic Calciustolls, and soils on the gently sloping treads are Lithic Haplustepts, Lithic Calciustepts, Lithic Calciustolls, and Lithic Petrocalcic Calciustolls (Wilcox et al., 2007). Vegetation includes oak trees, woody plants (mesquite, cypress, buttonbush), and grasses (switchgrass, bluestem grass, buffalograss) and forbs that are well-suited for grazing. The soils are not appropriate for agriculture due to high erosion rates and low water retention capacity (Woodruff et al., 2008). The average annual temperature is about 18°C and the average annual rainfall is about 76 cm (www.usclimatedata.com; accessed April, 2016).

Five soils of varying texture were collected from sites in Gillespie County, Texas (Figure 3.2). Samples were collected using a coring tool with a known volume, allowing determination of the field bulk density. Samples were all collected to support the Texas Soil Observation Network (TxSON). TxSON is an intensely monitored area (1300 km^2) of 41 monitoring stations located in Gillespie County, near Fredericksburg, Texas (Figure 3.2). The grid location was determined through mean relative difference (Cosh et al., 2007) of SWC from the North American Land Data Assimilation System (NLDAS-2) across each Hydrologic Unit Code (HUC8) within the Middle Colorado basin (Figure 3.3a). Sub grid locations at 3 km and 9 km cells were chosen based primarily on land accessibility and secondarily on soil type and geomorphic setting, including soil thickness, bedrock geology, and terrain.

These soils were chosen because they are representative of the field site and they vary in soil textural components, which will be discussed further below, and they represent a range of soil water characteristics in the field, as based on the mean relative difference (MRD). The MRD is used to analyze and compare the spatial variability of SWC across spatial scales and under different conditions (Mittelbach et al., 2012). This method aims at identifying the most representative site to monitor SWC within a given network. This method was used to select the five soil types that were analyzed in this research (Figure 3.3b). The five soils were collected from the top 10 cm of the soil profile and include Bastrop loamy fine sand, Luckenbach clay loam, Hensley loam, Okalla silty clay loam, and Purves clay. Using the USDA-NRCS Official Soil Series Descriptions (2015), the Bastrop loamy fine sand (BaC) consists of a very deep, well drained, moderately permeable soil formed in loamy alluvium derived from the Quaternary age sandstone and shale. The Luckenbach clay loam (LuB) consists of very deep, well drained, moderately slowly permeable soils that formed in ancient loamy or clayey alluvium. The Hensley loam (HnD) consists of well drained, non-calcareous soils that are shallow on indurated limestone of Lower Cretaceous and Pennsylvanian age. The Oakalla silty clay loam (Fr) consists of very deep, well drained soils that formed in loamy alluvium derived from limestone of Cretaceous age. The Purves clay (PuC) consists of shallow, well drained, moderately permeable soils that formed from interbedded limestone and marl.

The soil samples were first oven-dried for 24 hours at 105°C and passed through a 2 mm sieve. Samples preparation for particle size analysis involved preparing a mixture of 0.5 g soil, 5 ml of hydrogen peroxide (30%) concentration, 25 ml sodium hexametaphosphate solution (5% concentration), and shaking for 24 hours (using a mechanical shaker), allowing one hour to settle before measurement. The hexametaphosphate was used as both a dispersant and surfactant to de-clump the particles, and the peroxide was used to break down the organic matter, which can bind to clay particles therefore underestimating the clay content (Day 1965). Then, a laser particle size analyzer (model Mastersizer 3000, Malvern Instruments Ltd., UK) was used to analyze the soil particle size of the soil materials ranging from 0.1 μm to 2000 μm in diameter. The laser diffraction measurement works by passing a laser beam through a dispersed soil sample and measuring the angular variation in intensity of the scattered light (Gee et al., 2002).

A portable meter (model HI991300, Hanna Instruments, Woonsocket, RI) was used to measure soil EC and pH following Thomas (1996). Sample preparation for measuring EC included mixing 5 g of soil with 25 ml of de-ionized water (1:5 soil:water ratio) in a 50 ml centrifuge tube, shaking (using a mechanical shaker) for approximately 30 minutes, and then allowing the solids to settle for 30 minutes before measuring the supernatant liquid (Rhoades, 1996). The probe was then submerged into the sample until a stable reading was observed. The probe was rinsed thoroughly between measurements to eliminate cross-contamination. Sample preparation for measuring pH included mixing 5 g of soil with 10 ml of a 0.01 M calcium chloride dihydrate solution (1:2 soil solution ratio) in a 50 ml centrifuge tube, shaking (using a mechanical shaker) for approximately 30 minutes, and then allowing the solids to settle before measuring the supernatant liquid (Thomas, 1996). The probe was then submerged into the sample and swirled until a stable reading was observed. The probe was rinsed thoroughly between measurements to eliminate cross-contamination.

3.2.2 Sensor Calibration

All experiments for the three calibration methods were conducted in the laboratory at an ambient temperature of approximately 22°C. In each case, the sensor was connected to a data logger (model CR1000, Campbell Scientific Inc., Logan, UT) for data acquisition. Each experiment was conducted using the same test cell, which was a 12 cm diameter, 30 cm long polycarbonate container. For all 3 methods, the soil columns were packed using the same procedure, but at different water contents depending on the method (described below, when applicable).

3.2.2.1 Standard Calibration

The standard calibration method (Topp et al., 1980; Nadler et al., 1991; Dirksen et al., 1993) for electromagnetic probes consists of step-wise increase of SWC while taking multiple measurements of the sensor's response. For standard calibration, a known volume of water was added to the soil sample, mixed thoroughly, and then stored overnight in an airtight plastic bag to equilibrate. Soil for each experiment was packed to uniform bulk density by roughly separating the soil into 3 equal portions, adding and tamping (compacting) one lift to the container at a time until enough soil is added to cover the length of the probe (12 cm). Before placing successive layers, the top of the existing compacted layer was loosened to better blend one soil layer to the other, thus avoiding barriers to flow; this process was then repeated for the remaining layers. After the column was packed with soil, the sensor was inserted vertically and measurements were collected. This process was repeated for each soil type for each of four increasing water content steps. At the end of each experiment, all soil was removed from the column and placed in a drying oven for at least 24 hours at 105°C. Volumetric water content (θ_v) was then calculated as the product of gravimetric water content (θ_g) and bulk density (ρ_b), which was calculated from the dry mass of the soil and the container volume.

3.2.2.2 Upward Infiltration

Upward infiltration experiments (Hudson et al., 1996; Young et al., 1997) were completed in triplicate for each of the five soils (15 experiments in total), using the same soil column and packing procedure described above. The experimental set up is shown in Figure 3.4. After the column was packed with the soil, and placed on a digital scale, the CS655 was inserted vertically and measurements were collected. Rather than measuring change in mass of the water reservoir, as done by Young et al. (1997), here we installed a differential pressure transducer (PX170, Omega Engineering) in the Mariotte column and connected it to the data logger. Pressure head data were collected every 2 minutes and converted to change in water volume using the inside diameter of the Mariotte (4.45 cm). As the experiment progressed, the wetting front migrated upward and the average water content of the soil surrounding the probe increased until saturation was reached. Manual measurements of column mass during the experiments were taken to back-check the loss of water from the Mariotte column. Volumetric water content throughout the experiment was determined by subtracting the water mass added to the column from the final mass of the column after the experiment was completed.

3.2.2.3 Downward Infiltration

Here, soil was originally packed into the columns at a uniform volumetric water content of 0.05 m^3 m^{-3}. Only one experiment per soil type was completed (5 experiments total). After the column was packed with the soil, and placed on a scale, the CS655 was inserted vertically and readings were taken accordingly. Water was then added manually to the top of the column, increasing the SWC by 0.04 m^3 m^{-3} for each step, until saturation was reached. Water was added slowly allowed to infiltrate and equilibrate completely before adding the next amount. Evaporation was minimized by sealing the core with parafilm wax between water additions. The final water contents were verified at the end of each test gravimetrically.

3.2.3 Data Analysis

The results of each experiment yielded paired values of dielectric permittivity and SWC. A third-order polynomial of the form of Topp et al. (1980) was used to fit the data. Comparisons were made between the observed water content using the measured amount of water added during the experiments, the water content recorded by the sensor (using Topp's equation), and the water content calculated from the third-order polynomial fitted to the measured dielectric constant.

The root-mean-square error (RMSE) and the coefficient of determination (r^2) were used to evaluate the differences between the observed volumetric water content and the estimated volumetric water content. An analysis of variance (ANOVA) test was used to statistically compare the five soil types and the three calibration methods. In the former, replicated measurements (in the case of upward infiltration) were first compared for similarity using a Repeated Measures ANOVA on Rank (Tukey Test) using SigmaPlot (version 13) to identify potential outliers; for those results found to be similar, data from each upward infiltration experiment were used to simultaneously fit a single calibration curve for each soil types (i.e., a global curve), which was then compared to the average factory curve that uses Topps' equation. The goal was to determine if the single calibration curve obtained from each method differed from the factory curve, thus pointing to the need for soil-specific calibration. In the latter, we compared the calibration curve obtained by each method for each soil type to the factory curve. This was done by fitting a single calibration curve to data from all three experiments, holding each soil constant. We then compared the soil-specific curve to Topp's equation.

All comparisons were done using the ANOVA (parametric and non-parametric, as described below), with a significance level of 0.05.

3.3 RESULTS

3.3.1 Soil Properties

The physiochemical properties of the investigated soils are presented in Table 3.3. The five soil types vary by texture, with BaC and HnD having the highest sand content and lowest clay content. LuB and Fr have the next highest sand content and lowest clay content with over 30% silt. PuC has the lowest amount of sand and the highest amount of clay (16.8%). The EC was generally low with moderate increase with increasing clay content, with PuC having the highest EC (0.14 dSm^{-1}) and BaC and HnD having the lowest EC (0.10 dSm^{-1}). pH also typically increases with increasing clay content. PuC has the highest pH (7.58), and BaC and HnD have lower pH values. However, LuB has a higher clay content compared to BaC and HnD, but has a lower pH. This could be due to other factors besides texture that influence pH, such as organic matter.

3.3.2 Sensor Calibration

Table 3.4 lists the minimum and maximum volumetric water contents for all three methods and the average bulk densities for the standard calibration and upward infiltration methods and the actual bulk density for the downward infiltration method. The table shows some variability in bulk density for the same soil type for different methods, in part because of the difficulty in repeated repacking of soil material at the same bulk density as the water content increases. These differences were largest in the BaC soil but were relatively constant in the other four soils tested. Figures 3.5a-c show volumetric water content as a function of dielectric permittivity using all three calibration methods and isolating the five soil types. The results for the standard calibration (Fig. 3.5a and Table 3.5) show a similar concave shape for all soil types, with the global curve representing the data well ($r^2 = 0.921$, RMSE = 0.026). Some differences to Topp's equation are evident, with Topp's equation underestimating water content at the dry end and overestimating water content at the wet end. The findings for downward infiltration (Fig. 3.5c) were nearly the same. Thus, combining both the standard and downward data results in a site-specific calibration that improves performance ($r^2 = 0.933$, RMSE = 0.026 $m^3\ m^{-3}$) over the corresponding Topp coefficients used by the manufacturer ($r^2 = 0.930$, RMSE = 0.050 $m^3\ m^{-3}$).

Results for upward infiltration (Fig. 3.5b) were quite different, however, with the overall shapes of the permittivity-water content response appearing as concave upward, except for the BaC soil, which appears to more closely follow the Topp's equation. The responses for the HnD and PuC soils also show large upward trending in water content toward the wet end. The explanation for this behavior is not readily apparent, and it was seen in all replicated experiments (not all shown). Thus, the potential exists that the sharp wetting front near the handle of the probe could cause some instability in the permittivity readings, and hence some caution is advised in assuming the Topp's curve represents the global response of soils. These results also show some differences in calibration coefficients as a function of laboratory method. Using the ANOVA test, results indicate a significant difference between methods ($p<0.05$).

Figures 3.6a-c show electrical conductivity responses as a function of the dielectric permittivity using all three calibration methods and isolating the five soil types. Electrical conductivity increases with SWC. The standard calibration method (Fig. 3.6a) and the downward infiltration method (Fig. 3.6c) yield similar EC values. The upward infiltration method (Fig. 3.6b) underestimates the EC and therefore the resultant SWC is much lower until the wetting front moves closer to the sensor head. Figures 3.7a-c show SWC responses as a function of the EC using all three calibration methods and isolating the five soil types. EC increases with increasing clay and SWC. Similar to Figures 3.6a-c, the standard calibration method (Fig. 3.7a) and the downward infiltration method (Fig. 3.7c) yield similar electrical conductivity values and the upward infiltration method (Fig. 3.7b) underestimates the electrical conductivity.

Figures 3.8a-e show water content responses as a function of the dielectric permittivity, plotted separately for each soil type, for all three calibrations, and the fitting coefficients are found in Table 3.5. The results show large differences between the fitted calibration curve and the Topp's equation for all soils tested, except the BaC soil (Fig. 3.8a), in which case the curves nearly overly one another. The differences in shape and position of the other fitted curves are mostly due to the impact of the upward infiltration method, which appears to pull down the calibration curve. When the upward infiltration data are removed, the fitted curves using data from the standard calibration and downward infiltration methods are much closer in shape to Topp's curve. The RMSE and r^2 found in Table 3.5 also improve when the upward infiltration data are removed. The RMSE and r^2 for every experiment are presented in Table 3.6. As discussed above, the upward infiltration method may not be ideal for calibrating the CS655 sensor. The results also show that the CS655 sensor, in general, underestimates the volumetric water content at low water contents (< 0.15 $m^3\ m^{-3}$) and overestimates the volumetric water content at high water contents, when compared to the factory-supplied calibration curve. This disparity is especially prevalent in the soils with higher clay contents (i.e., Purves [PuC] clay).

3.4 Conclusions

The performance of the factory-supplied calibration equation for volumetric water content was evaluated for the CS655 water content reflectometer in five well-characterized soils using three different calibration methods. Results indicate that the soil-specific calibration curves are more accurate than the factory calibration (Topp's) and that these soil-specific calibrations are more appropriate than a global calibration curve for the CS655. This study establishes that the upward infiltration method is not the best calibration method due, most likely, to the sharp wetting front when used with the CS655 sensor. The standard calibration and downward infiltration methods are better options and were found to be similar in shape and magnitude. However, the standard calibration requires re-packing of the soil column several times, which could lead to bulk density variability that could affect the results. The downward infiltration method may be the best method to use to calibrate the CS655. This method led to a strongly significant correspondence (r^2 = 0.924; RMSE = 0.026 m^3 m^{-3}) when used in this study.

Table 3.1 Equations for calculating volumetric water content using the CS655 sensor. Equation numbers here are referenced in Fig. 1.

	Equation
1	$\sigma_0 = C_0 + C_1\alpha + C_2\alpha^2$
2	$\sigma = EC_{mult} * \sigma_0 + EC_{offset}$
3	$\epsilon_a = C_0\sigma_b^3\tau^2 + C_1\sigma_b^2\tau^2 + C_2\sigma_b\tau^2 + C_3\tau^2 + C_4\sigma_b^3\tau + C_5\sigma_b^2\tau + C_6\sigma_b\tau + C_7\tau + C_8\sigma_b^3 + C_9\sigma_b^2 + C_{10}\sigma_b + C_{11}$
4	$K_a = Ka_{mult} * Ka_0 + Ka_{offset}$
5a	$\theta = -0.0053 + 0.0292K_a - 0.00055K_a^2 + 0.0000043K_a^3$ (Topp Eq.)
5b	$\theta = -c0 + c1K_a - c2K_a^2 + c3K_a^3$ (user specified calibration coefficients)
6	$\sigma_{25} = s/(1 + 0.02 * (T_{soil} - 25)$

Table 3.2 CS655 Coefficients used by the CS655 to calculate permittivity (Ka).

	Low Ka	High Ka	Ka Limit
C0	-1.26445	10.7675	6.20428
C1	13.0204	-61.1631	12.4027
C2	-5.12193	52.4812	1.5248
C3	21.1534	23.3351	-4.77748
C4	4.55704	-45.6511	2.18093
C5	-45.0505	278.607	-0.25789
C6	30.0966	-228.748	
C7	-29.8127	-36.6825	
C8	-5.28148	46.5711	
C9	34.7272	-316.726	
C10	-37.5712	251.335	
C11	9.02086	13.7252	

Table 3.3 Physiochemical properties of investigated soils.

Soil	Sand	Silt	Clay	ρ_b*	ϕ†	EC	pH
	---------------- % ----------------			g cm^{-3}	--	dS m^{-1}	--
BaC	79.0	16.9	4.9	1.26	0.52	0.10	6.97
LuB	52.5	33.7	13.8	1.50	0.43	0.13	6.90
HnD	79.3	17.6	3.1	1.26	0.52	0.10	6.81
Fr	54.0	35.1	10.9	1.29	0.51	0.13	7.50
PuC	33.7	49.5	16.8	1.11	0.58	0.14	7.58

* Bulk density was measured in the field.

† Porosity = 1 – (bulk density/particle density), assuming particle density =2.65 g cm^{-3}.

Table 3.4 Experiment parameters including minimum and maximum volumetric water content and bulk density.

	Standard Calibration			Upward Infiltration			Downward Infiltration		
	θ		ρ_b*	θ		ρ_b*	θ		ρ_b*
Soil	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Actual
	-------$m^3\ m^{-3}$---------		$g\ cm^{-3}$	--------$m^3\ m^{-3}$--------		$g\ cm^{-3}$	-------$m^3\ m^{-3}$--------		$g\ cm^{-3}$
BaC	0.100	0.250	1.59	0.001	0.323	1.64	0.050	0.290	1.46
LuB	0.100	0.400	1.18	0.002	0.389	1.23	0.050	0.370	1.10
HnD	0.100	0.400	1.14	0.003	0.393	1.27	0.050	0.370	1.26
Fr	0.100	0.400	1.19	0.009	0.396	1.22	0.050	0.370	1.23
PuC	0.100	0.400	1.09	0.000	0.399	1.14	0.050	0.370	1.15

* ρb = mass of soil/volume of container

Table 3.5 Coefficients for Equation 5b in Table 3.1 and statistical results.

Method	c0	c1	c2	c3	r^2	RMSE $m^3 m^{-3}$
Standard	6.77E-02	1.72E-02	-2.32E-04	0	0.929	0.026
Downward Infiltration	2.05E-02	2.16E-02	-3.20E-04	0	0.924	0.033
Upward Infiltration	1.23E-02	1.27E-02	0	0	0.881	0.045
Standard & Downward (combined)	3.37E-02	2.05E-02	-2.98E-04	0	0.933	0.026
Topp Equation	-5.30E-02	2.92E-02	-5.50E-04	4.30E-06	0.930	0.050

All Methods

Soil	c0	c1	c2	c3	r^2	RMSE
BaC	-6.49E-05	1.62E-03	9.44E-03	-3.52E-03	0.921	0.026
LuB	9.25E-06	-4.42E-04	1.76E-02	1.81E-02	0.843	0.069
HnD	2.39E-05	-9.39E-04	2.40E-02	-2.73E-02	0.877	0.063
Fr	7.56E-06	-2.97E-04	1.45E-02	1.69E-02	0.773	0.084
PuC	9.63E-06	-6.42E-04	2.18E-02	-1.03E-03	0.896	0.087

Standard Calibration and Downward Infiltration

Soil	c0	c1	c2	c3	r^2	RMSE
BaC	4.61E-05	-1.94E-03	3.84E-02	-3.41E-02	0.943	0.030
LuB	2.11E-05	-1.34E-03	3.43E-02	1.07E-02	0.957	0.059
HnD	1.60E-05	-9.35E-04	2.87E-02	-1.06E-02	0.948	0.036
Fr	3.36E-05	-1.89E-03	4.26E-02	3.30E-02	0.958	0.046
PuC	9.72E-06	-8.17E-04	2.75E-02	8.57E-03	0.955	0.055

Table 3.6. R^2 and RMSE for all soils and all methods.

	Standard		Upward		Downward	
Soil	r^2	RMSE	r^2	RMSE	r^2	RMSE m^3 m^{-3}
BaC	0.942	0.041	0.994	0.026	0.994	0.022
LuB	0.950	0.060	0.927	0.038	0.959	0.059
HnD	0.920	0.055	0.971	0.030	0.975	0.023
Fr	0.943	0.053	0.901	0.047	0.970	0.043
PuC	0.942	0.071	0.876	0.034	0.976	0.047

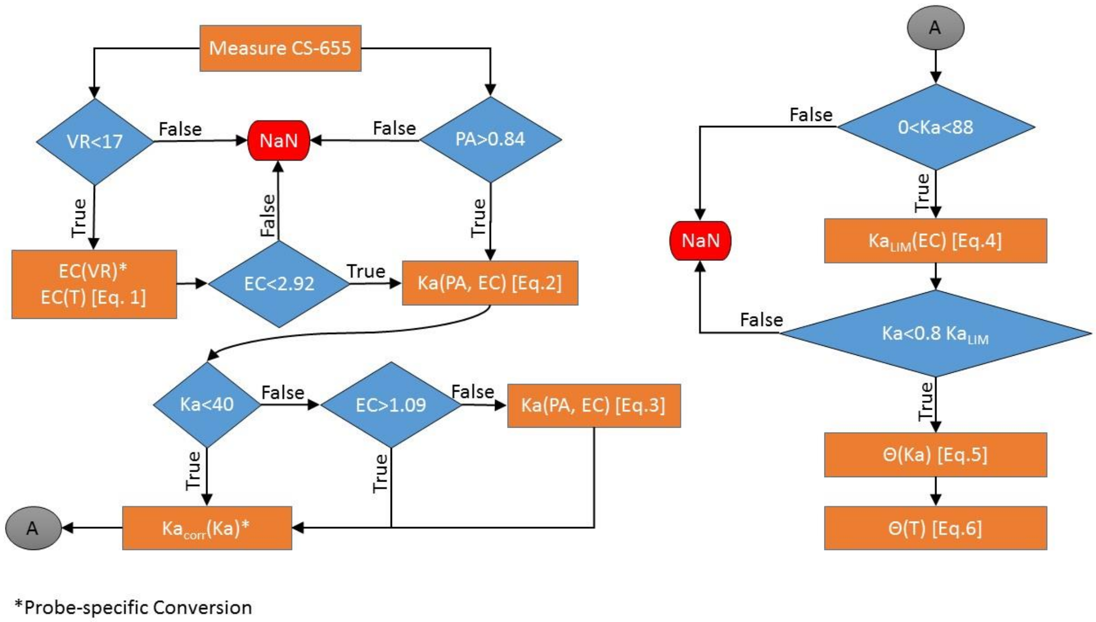

Figure 3.1. Schematic for operations of CS655. Symbols are defined as Ka = permittivity, θ = volumetric water content, EC = electrical conductivity, PA = period, VR = voltage ratio, T = temperature and NAN = Not a Number. Equations are listed in Table 3.1.

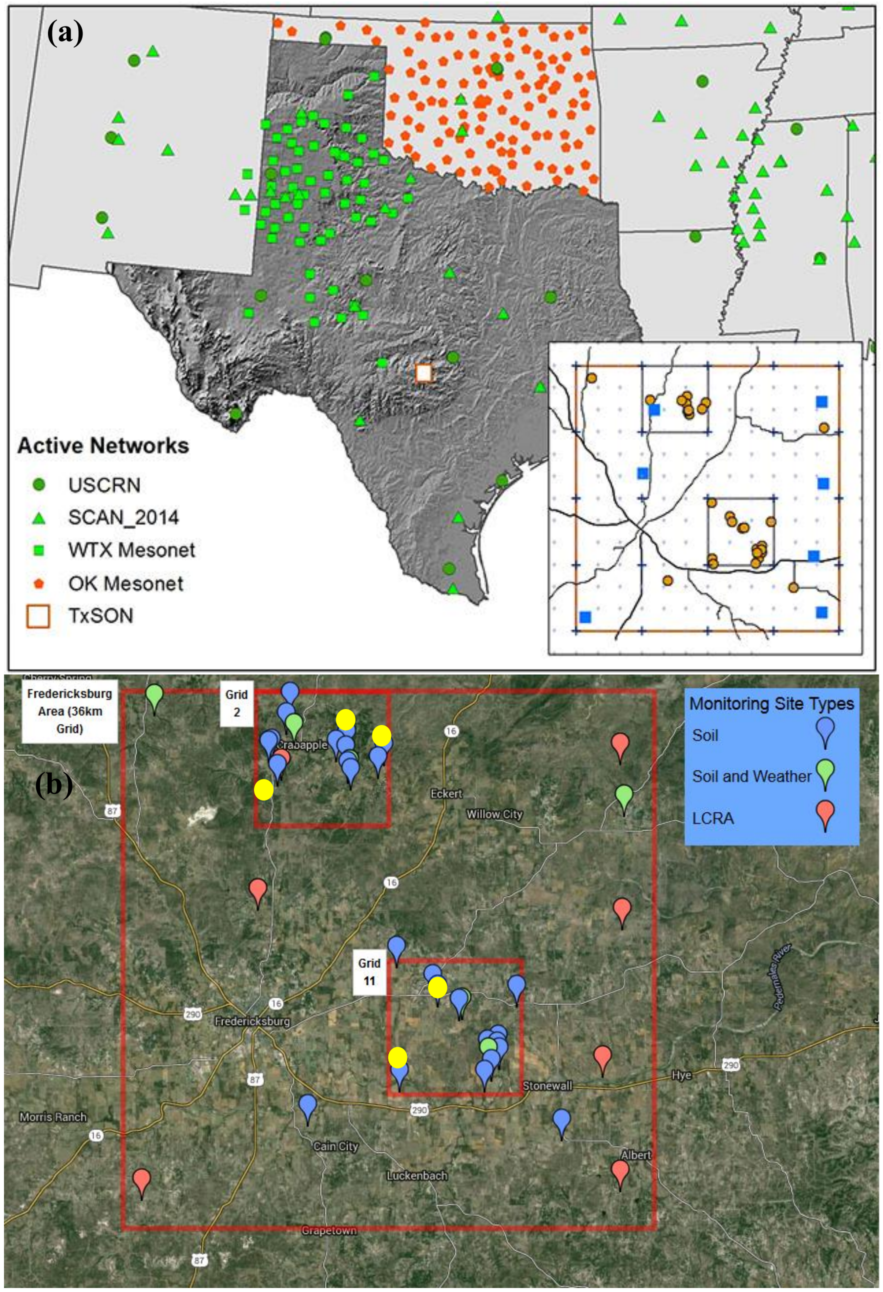

Figure 3.2. (a) The TxSON locations in comparison to other related active soil moisture monitoring networks. (b) The 41 field site locations within TxSON in Gillespie County. (source: www.beg.utexas.edu/txson/) Yellow dots represent locations where soils were collected. Clockwise: BaC, LuB, Fr, HnD, PuC.

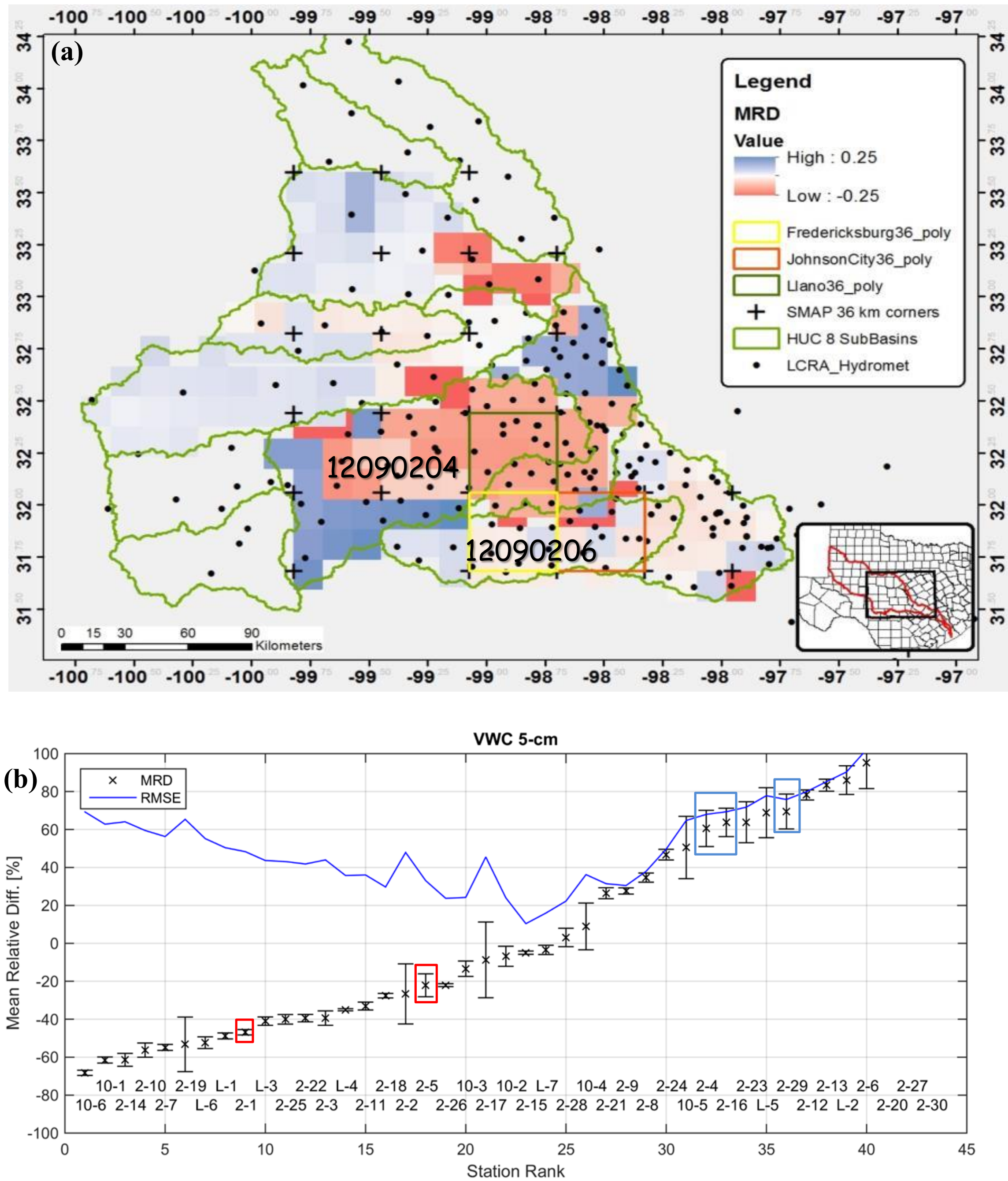

Figure 3.3. (a) MRD using NLDAS-2 within each HUC 8. (b) Mean relative difference (MRD) for the TxSON *in-situ* data over a 9 month period beginning on 1 December 2014. Red boxes represent drier soils, blue boxes represent wetter soils chosen for this study.

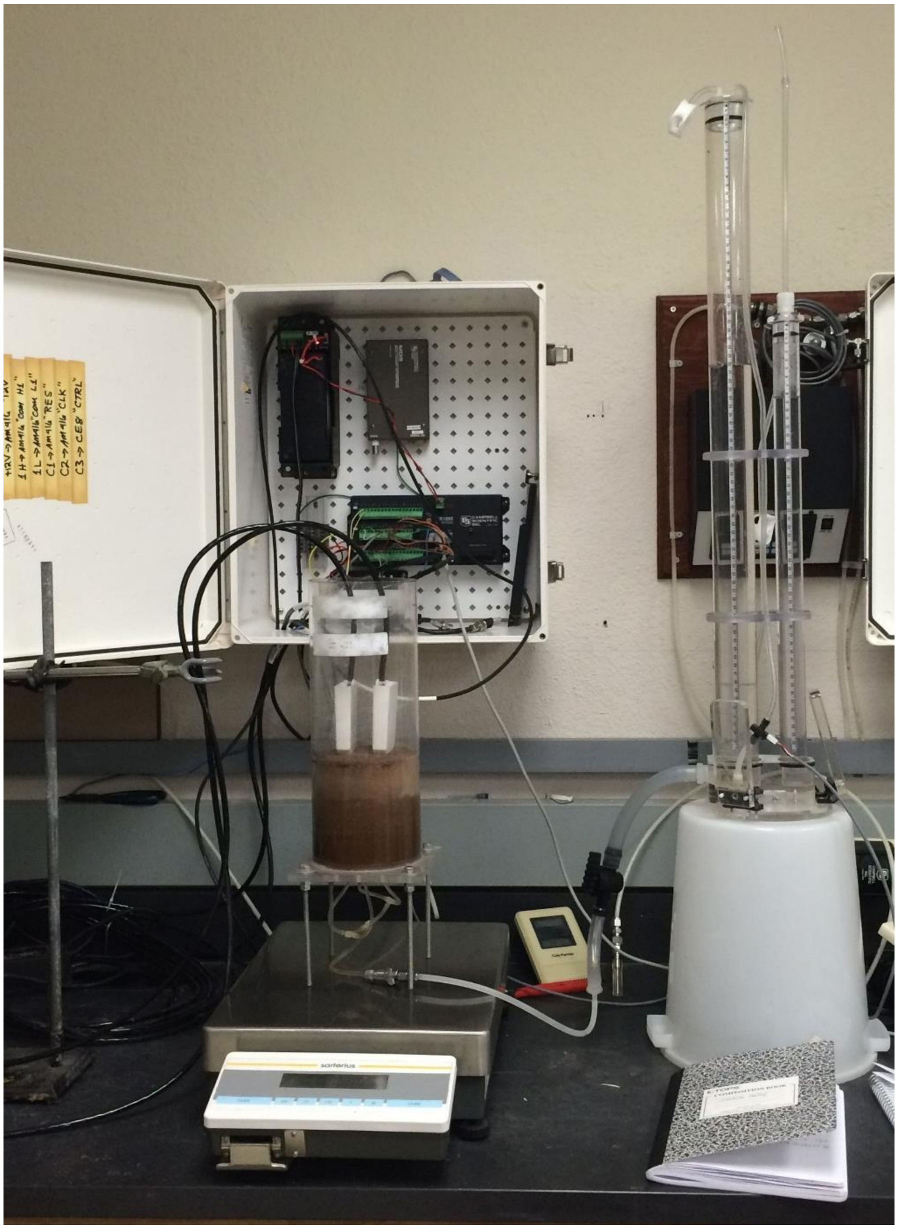

Figure 3.4. Experimental set up of an upward infiltration experiment. The Mariotte system (right) supplies water under tension into the bottom of the soil core (left) where two CS655 sensors measure permittivity. The core rest on a scale and all data are recorded on the data acquisition system in the rear.

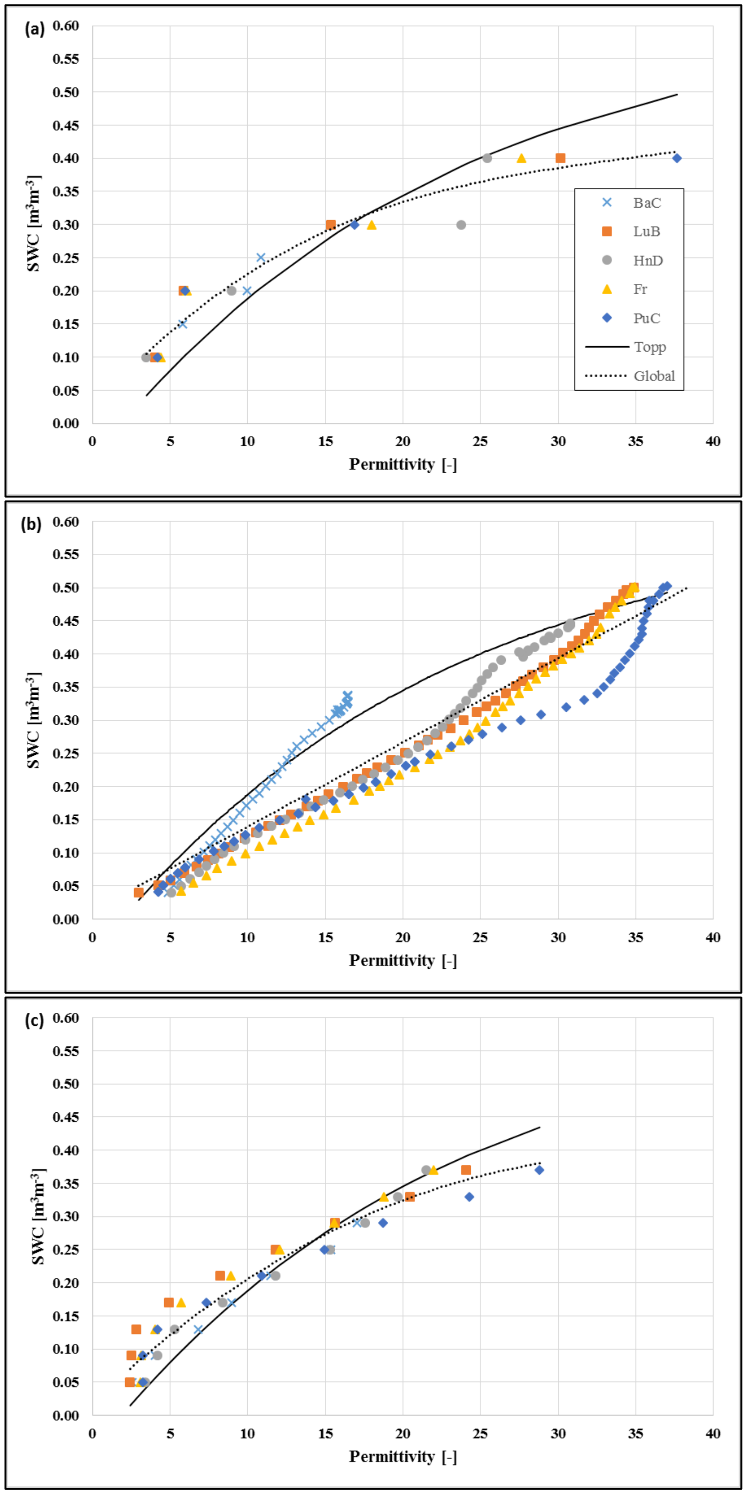

Figure 3.5. Global calibration curves for the (a) standard calibration, (b) upward infiltration, and (c) downward infiltration methods.

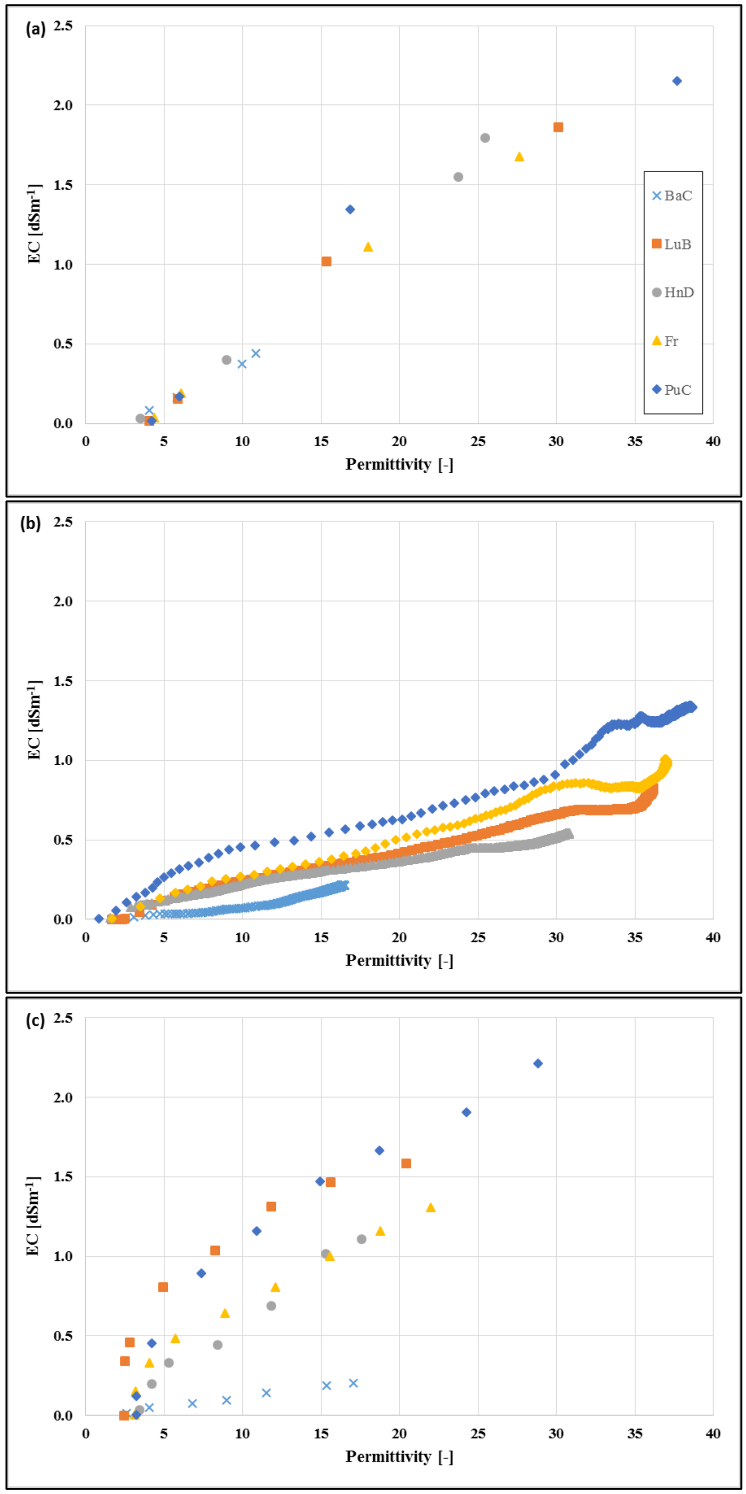

Figure 3.6. Electrical conductivity (EC) as a function of permittivity for the (a) standard calibration, (b) upward infiltration, and (c) downward infiltration methods.

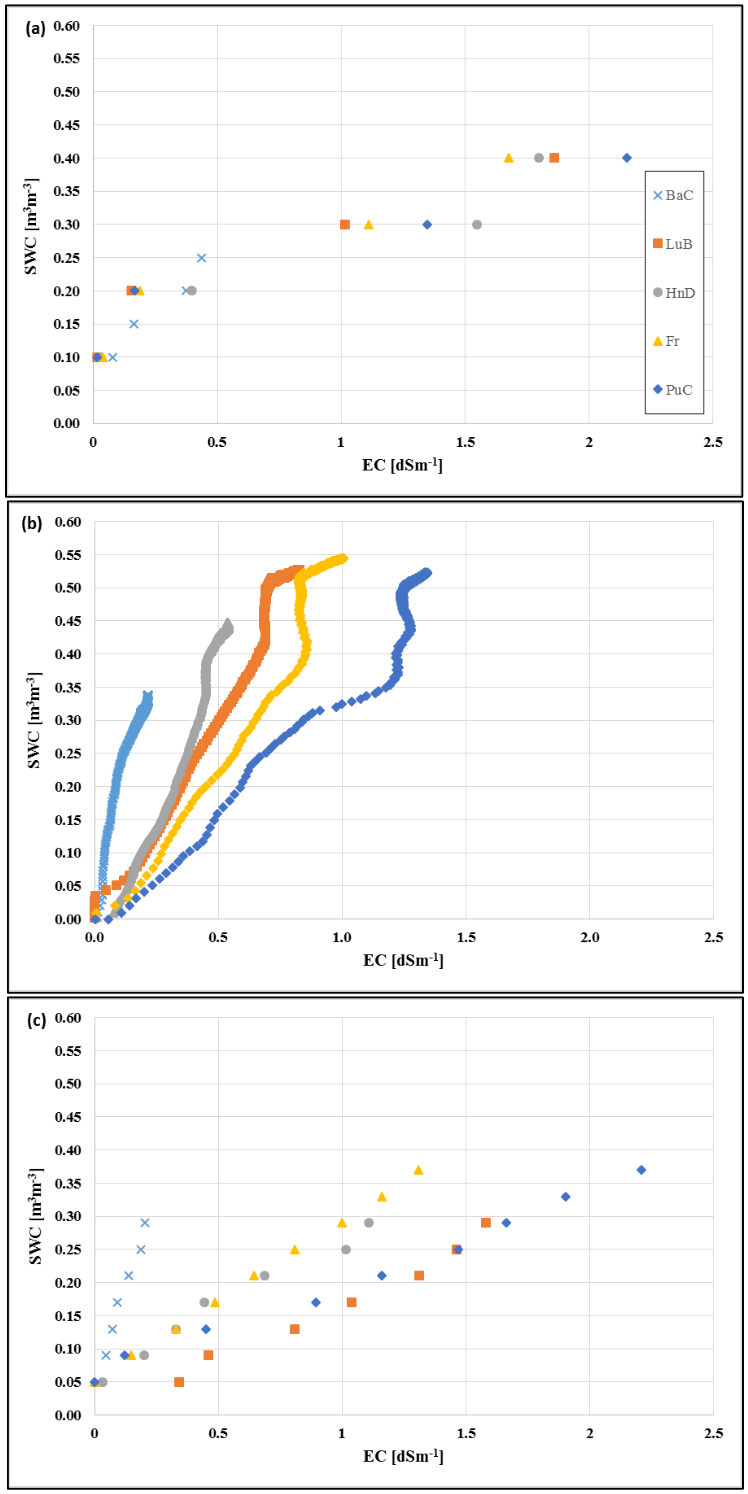

Figure 3.7. Soil water content (SWC) as a function of electrical conductivity (EC) for the (a) standard calibration, (b) upward infiltration, and (c) downward infiltration methods.

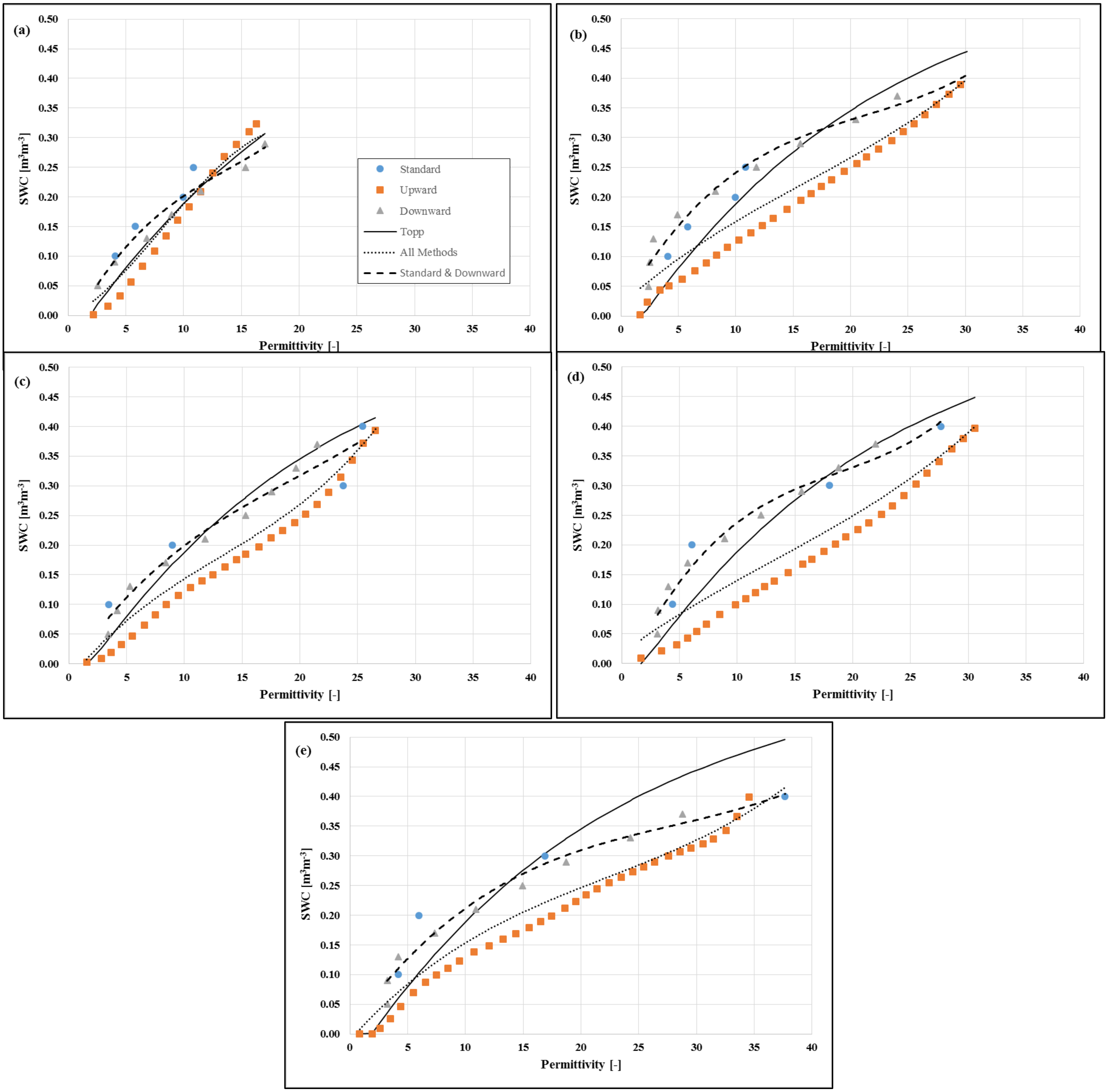

Figure 3.8. Soil specific calibration curves for all methods and the standard calibration and downward infiltration methods for the (a) BaC, (b) LuB, (c) HnD, (d) Fr, and (e) PuC soil types.

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Chapter 4: Discussion

4.1 Limitations and Uncertainties

Limitations and uncertainties with the CS655 exist both in SWC measurements and the calibration methods described in Chapter 3. One such limitation is the temperature dependence of the soil on the dielectric permittivity measurements. The temperature effects on the operation of the probe electronics is minimal, with period average readings varying less than 0.5% of a measurement taken at a standard 20°C, over the range of 10°C to 30°C, and less than 2% of a measurement taken at 20°C readings across the range of -10°C to 70°C (Campbell Scientific, 2015). The measurement is made using a thermistor located at the base of the epoxy sensor head and is in contact with one of the waveguides (Campbell Scientific, 2015). Therefore, the thermistor does not measure the average temperature in the soil along the waveguide (where the measurement is focused), but instead provides a point measurement of the temperature within the epoxy of the sensor head, a potential shortcoming if the environment at the probe head is not representative of environment measured at the waveguides (e.g., near surface soil where waveguides are buried deeper than the probe head). Unfortunately, no general equation corrects volumetric water content for temperature for all soils. However, the effect of temperature can be compensated for by converting the electrical conductivity measurements, which is used to estimate water content, to a standard, 25°C using the following equation (Campbell Scientific 2015):

$$EC_{25} = EC_T / (1 + 0.02*(T_{soil} - 25) \qquad \textbf{4.1}$$

where EC_{25} is the bulk electrical conductivity at 25°C and EC_T is the bulk electrical conductivity at the soil temperature (°C) (Campbell Scientific, 2015). This temperature correction is the last step in estimating the volumetric water content performed by the sensor (as shown in Figure 3.1) and is listed in Table 3.1 with the other equations used by the sensor.

The sensing volume of the probe could also be considered a limitation. The sensing volume of the CS655 is 3600 cm^3, a volume estimated assuming a 7.5 cm radius around each waveguide, and extending 4.5 cm beyond the end of the rods. Depending on the problem at hand, this relatively small volume may or may not represent the area or process being studied. However, the potential non-representativeness of point measurements can be reduced by increasing the number of measurements made across the study area, or by ensuring that each probe location represents the largest possible area.

Other sources of uncertainty can become significant due to sensor installation. The probe waveguides must be inserted into the soil as close to parallel as possible to maintain the design of the waveguide geometry (Campbell Scientific, 2015). The CS655 must be inserted in a steady manner to prevent air voids, which reduce measurement accuracy. Air voids around the waveguides would yield lower water content values, because air has a lower permittivity than water. Gaps around the waveguides could also create preferential pathways for water flow, thus disrupting natural percolation. The bulk density of the samples used in the laboratory experiments should be close to the field bulk density to accurately represent the soil condition. The uncertainty from probe installation may differ depending on the experiment. For example, in the upward and downward infiltration experiments, the probe is inserted into the soil column at the beginning of the experiment and is not removed until the experiment is finished. Therefore, any errors associated with probe insertion or bulk density variations are uniform throughout the entire experiment, creating a bias in all measurements. The standard calibration experiments require a new soil column to be packed and the probe to be re-inserted at each step for each water content that is measured. Therefore, uncertainties could vary at each water content step.

Furthermore, the bulk densities may differ slightly from one water content to another during standard calibration, but are constant during the upward infiltration and downward infiltration experiments.

Wetting fronts during the laboratory experiments could be a source of error. Specifically, the results of the upward infiltration experiments and the downward infiltration and standard calibration experiments differed significantly, and this points to a potential probe-technology-specific explanation. We noted, for example a generally convex upward shape of the calibration curve when fitting the third-order polynomial to the dielectric constant-water content data obtained from the upward infiltration experiments. Though the fits to the polynomial, in general, were quite good, the shape of the calibration curve differs from Topp's equation, and the results of the downward infiltration and standard calibration experiments. The upward infiltration experiments lead to wetting fronts that are likely sharper than downward infiltration, where gravity and matric potential gradients can result in diffuse wetting fronts. If the probe electronics are susceptible to large impedance mismatches from wet and dry soils, then the upward infiltration may not be an acceptable method of calibration, even given the experimental upsides.

4.2 The Future of Soil Monitoring Networks

SWC has a high spatial and temporal variability as discussed in previous chapters. SWC monitoring networks that provide constant measurements at multiple scales, such as the point-scale and the watershed scale, can provide insight into the soil water conditions of larger areas. The objective of soil monitoring networks, such as TxSON, is to overcome the spatial and temporal challenge of monitoring systems by providing real-time measurements of SWC over a range of spatial scales. This can be especially useful in drought-prone states like Texas, where the soil moisture deficit in times of drought making is important to quantify and understand. TxSON, and other networks like it, aim to measure SWC at a scale so it can be applied to address many other scientific questions, such as climate prediction, water resources management, improved irrigation scheduling, and the water and energy balance.

The comparison of *in-situ* soil moisture data and satellite remote sensing data also helps with the issue of spatial variability. *In-situ* soil monitoring networks can be used to calibrate and validate satellites that use remote sensing technology to estimate water content, such as NASA's SMAP satellite mentioned previously. Ochsner et al. (2013) present a review and analysis of large-scale soil monitoring networks. This review highlights the lack of standards for sensor calibration, installation, and *in-situ* validation as a significant challenge of monitoring SWC. Ochsner et al. (2013) was published before the launch of SMAP, but does mention SMAP's mission to measure surface SWC (~5 cm) and emphasizes its ability to do so accurately with proper calibration and validation. The largest effort in soil moisture monitoring right now seems to be devoted to the advancement of satellite remote sensing approaches (Ochsner et al., 2013). With the advancement of satellite remote sensing, ground truthing remains relevant as a way to validate this evolving technology.

4.3 Final Statements

This research presents three different methods used to calibrate the CS655 water content reflectometer, thus improving the accuracy of measurements in comparison to Topp's equation (Topp et al., 1980). Results indicate that the soil-specific calibration curves obtained for the five soil types are more accurate than the factory (i.e., Topp's) calibration. This research verifies that soil-specific calibration for this electromagnetic sensor is necessary to improve the accuracy of measurements since they are dependent on soil characteristics. The calibration methods presented here can be used by future users to improve field-based measurements and more accurately represent SWC across various soil types.

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